KEYNOTE ADDRESS

Global Trends in the Development of Rodenticides and Mammalian Pest Control Technologies

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ABSTRACT: The history of discoveries in rodenticide development and control technology as well as current and future-focused research are explored. Traps and older poisons such as red squill, arsenic, and cyanide have been used for hundreds if not thousands of years. Between 1940 and 1980 there was a period of innovation with the discovery of new molecules, including acute toxins and slower acting anticoagulants. The period 1980 to 2018 has been a time for improved utilization of individual tools and research to retain registrations, develop new toxins and delivery systems, and explore non-lethal control options. However, despite these advances, decades old broad-spectrum toxins and traplines are still the mainstay of pest control. Technological leaps are needed to achieve much more precise, affordable, and socially acceptable pest control. The period 2018 to 2050 should be a time for accelerated innovation. There are exciting opportunities for transformational change based on the integration of existing and new tools, such as advances in automated species recognition systems, new self-resetting traps, and species-specific toxin-delivery systems. Over-reliance on 'silver bullet' technologies for small mammal pest control is the wrong approach to biodiversity conservation. This has been demonstrated through two decades of challenging research on viral vectored immunocontraception, and would apply if all pest control research focused on a single toxin, one new engineering-based technology, or on gene editing, which has potential, but will not be a panacea for all mammal pests. Balance is important, with research supporting the skill of pest control practitioners and supporting emerging technologies, as well as novel biocontrol or genetic research. There has been no focused research aimed at integrating a broad suite of new tools, and incorporating disruptive technologies from completely different fields. We believe that science and technology have now advanced such that automated, online, and real-time systems for monitoring and managing pests are achievable in the next decade.

KEY WORDS: integration, pest control technology, rodenticides, transformation, trends

Proc. 28th Vertebr. Pest Conf. (D. M. Woods, Ed.)
Published at Univ. of Calif., Davis. 2018. Pp. 3-10.

INTRODUCTION

This paper specifically focuses on research aimed at advancing new vertebrate pesticides and pest control technologies with a historical and future focused lens. Traps and older poisons, such as red squill, arsenic, and cyanide, have been used for hundreds if not thousands of years. Reference to rodents being pests of granary stores, and subsequent attempts to control them, can be found in literature that goes back to many centuries BC (Gentry et al.1987, Prakash 1988). It is perhaps troubling, in terms of lure and trap development, that recommendations like baiting traps with peanut butter to manage rats today are the same recommendations found in the century old patent of the classic snapping mousetrap: In 1898 British inventor James Atkinson patented the classic snapping trap with a small metal plate with a dollop of peanut butter, which, when touched by the hungry rat, triggers a spring-loaded bar that strikes the rodent's neck with deadly force.

In terms of rodenticide development, there has been progress. It is noteworthy that compounds or chemicals derived from natural sources have inspired many ancient and modern medicines and biocides, including rodenticides and vertebrate pesticides. The chemical structures of natural compounds have evolved over millennia for specific biochemical purposes and they remain a foundation for developing new drugs and biocides. The importance of natural compounds is exemplified by the observation that over 60% of drugs are classified as "naturally-derived" (Cragg et al. 2009). Compounds used to control animal pests linked directly or indirectly to natural products include anticoagulants such as warfarin and brodifacoum; older poisons such as cyanide, strychnine, and red squill; and cholecalciferol

and sodium fluoroacetate.

Early Poisons

Prior to the First World War, there was reliance on natural toxins and some inorganics like zinc phosphide. Natural compounds used as poisons include strychnine, red squill, and cyanide. Strychnine is found in the seeds of the tree *Strychnos nux-vomica* (Pelletier and Caventou 1819). Strychnine was popularly used as an athletic performance enhancer and recreational stimulant in the late 19th century, and in the early 20th century, in low doses, as a tonic. It has been used, at higher doses, for rodent and vertebrate pest control since the mid-1800s (Schwartze 1922). Strychnine is a fast-acting compound and poisoned animals often die in less than one hour (though occasionally in 24 hours or longer) as a result of respiratory failure (asphyxia) (Osweiler et al. 1985).

Red squill, another very old poison, was extracted from bulbs of the Mediterranean plant *Urginea maritima* and has been used as a rodenticide and medicine (Gentry et al. 1987). It has been used as a medicinal plant since ancient times and is noted in the Ebers Papyrus of the 16th century BC, one of the oldest medical texts of ancient Egypt (Gentry et al. 1987). The bioactive substance in red squill is the cardiac glycoside, scilliroside. Its rodenticidal uses are summarised in earlier reviews (Hone and Mulligan 1982, Meehan 1984). Its primary medicinal use was as a treatment for eodema linked to cardiac failure (Hollman 1992).

Cyanide has been used in New Zealand for several decades to kill possums *(Trichosorus vulpecula)*, but has restricted use in other countries. Cyanogenic (cyanide-containing) compounds occur in plants and in some fungi and bacteria. More than 2000 plants are known to be cyanogenic, including food plants and forage crops. Young bamboo shoots and peach leaf tea are examples of dietary sources of HCN poisoning in children (Hayes 1994).

1940-1980

Between 1940 and 1980 there was a period of innovative chemistry with the discovery new molecules, including acute toxins and slower acting anticoagulants. Sodium fluoroacetate (1080) was developed in the 1940s; first generation anticoagulant rodenticides in the 1940s, '50s and '60s; and cholecalciferol and second generation anticoagulant rodenticides in the 1970s and 1980s, partly to overcome resistance to first generation anticoagulants that occurred overseas following prolonged use in agricultural or urban settings.

Fluorinated organic compounds are rare in nature but have been identified as the toxic agent in many poisonous plants native to South America (de Moraes-Moreau et al. 1995). As well as being natural toxins they have been extensively researched as rodenticides and for the control of other mammalian pests (Eason et al. 2011). 1080 was first synthesised in Belgium in 1896 but was not seriously investigated as a pesticide until the 1940s, when wartime shortages of strychnine and red squill stimulated its development (Atzert 1971). In the United States, 1080 is used solely for localised and very target-specific predator control in the Livestock Protection Collar (LPC), mainly to protect sheep (*Ovis aries*) against coyotes (*Canis latrans*). In Australia and New Zealand, it is formulated into baits to kill a range of introduced mammalian pests. New Zealand is the largest user of 1080 in the world, employing the active ingredient at the rate of ~1.0 to 3.5 tonnes per year (Innes and Barker 1999). The primary mode of action of 1080 is mediated via its toxic metabolite fluorocitrate, which inhibits the energy production in the tricarboxylic acid (Krebs) cycle.

Cholecalciferol (vitamin D_3) was developed as a rodenticide in the 1980s (Marshall 1984, Tobin et al. 1993). It is synthesised in animal skin by the action of sunlight on its precursor, 7-dehydrocholesterol. Natural dietary sources of vitamin D include liver, fish, fish oils, egg yolk, milk fat, and plants, and background levels are detectable in the blood and tissues of all mammals (Fairweather et al. 2015). The single-dose LD_{50} for cholecalciferol in Norway rats (*Rattus norvegicus*) and house mice (*Mus musculus*) is very similar (approximately 40 mg/kg); there is considerable species variation in susceptibility amongst other mammals; and possums are very susceptible. In New Zealand, cholecalciferol was first registered in the 1990s in baits at 0.4 and 0.8%, and in the United States at 0.1%. In Europe it was registered at 0.1% until this registration was discontinued, but re-registration is under consideration. The most distinguishing characteristic of cholecalciferol is its low risk of secondary poisoning of dogs (*C. familiaris*) and low toxicity to birds (Eason et al. 2000).

Prior to 1950, all vertebrate pesticides were non-anticoagulants, most of them acute or quick-acting, but after the introduction of warfarin and the other anticoagulants the importance of these non-anticoagulants was reduced, at least for rodent control. First-generation and second-generation anticoagulant rodenticides have the same mode of action: interference with the synthesis of blood clotting factors, which results in haemorrhaging and death. Over 10 anticoagulant agents have been synthesized, mostly between 1940 and 1980, and their principal use worldwide in pest control has been against commensal rodents, primarily Norway rats, ship rats (*R. rattus*), and house mice, for various field use applications, and in conservation programs.

The development of warfarin and related compounds is based on a chance observation, and subsequent detective work, nearly 100 years ago that linked haemorrhagic disease in cattle and sheep with grazing on sweet clover hay (*Melilotus alba* and *M. officinalis*) in the USA. The incidence of bleeding occurred most frequently when damp hay became infected by moulds such as *Penicillium nigricans* and *P. jensi*. The resultant bleeding disorder, which was known as sweet clover disease, became manifest within 15 days of ingestion and killed the animal within 30-50 days. After intensive research in the 1930s, the causative agent was isolated and identified. It was found that a natural coumarin became oxidized in mouldy hay, to form 3,3-methylene-bis[4-hydroxy-coumarin] commonly known as dicoumarol (Campbell and Link 1941). Research funded by the Wisconsin Alumni Research Foundation (WARF) led to exploration

of dicoumarol and coumarin derivatives between 1946 and 1948. Warfarin, number 42 out of a total of 150 synthesized analogues, was particularly effective and became a successful rodenticide.

After its success as a rodenticide, the transition of warfarin to clinical application was made, originally under the name Coumadin. The principal advantages of warfarin were its high water-solubility and high oral bioavailability. It was more potent than dicoumarol but retained the ability to have its effect reversed by vitamin K (Link 1959), another natural compound which might in nature have protected animals from mild coumarin toxicity. Following the emergence of resistance to first-generation anticoagulants, more potent compounds were synthesized. These include brodifacoum, which is also structurally related to a naturally occurring coumarin, and is now the most commonly used rodenticide worldwide, and has largely replaced warfarin for rodenticide applications. It is a very potent anticoagulant active against rodents, including those resistant to warfarin and other anticoagulants. A single ingestion of 1 mg/kg is usually sufficient to kill rodents. In New Zealand it is used principally to control possums and rats. Brodifacoum and related second-generation anticoagulants have unusual pharmacokinetics, namely a hepatic half-life of 150-300 days, which causes concerns related to bioaccumulation of brodifacoum in birds and other non-target species (Eason et al. 1999), and has been a driver for more research on strategies to reduce non-target exposure, including pulse baiting regimens and new technologies. Despite continuing residue concerns and non-target incidents (see publications in this Proceedings), anticoagulants have a long history of effective and comparatively safe use world-wide. It seems likely that anticoagulants will continue to dominate, or play a major role, for many years to come. If research could successfully identify a potent anticoagulant which is less persistent, it would be widely sought after.

1980-2018

The period 1980 to 2018 represents a time when field practitioners improved the application accuracy utilization of individual toxins and researchers retained registrations; developed additional toxins, lures, and delivery systems; and explored non-lethal control options. Improvements in the utilisation of individual tools can be illustrated by the aerial distribution of baits containing brodifacoum for one-off eradication operations on offshore islands. Brodifacoum in this setting has made a huge contribution to pest control and biodiversity conservation and is an effective and extremely important pest control tool pivotal to island pest eradication on islands programmes around New Zealand and worldwide (Parkes et al. 2017). It has transitioned over 30 years in New Zealand through stages of initial scepticism, to early accidental and experimental successes, and now to the current bold large-scale aerial applications over increasingly large and complex island ecosystems. Starting in the 1970s and 1980s, gaining momentum in the 1990s, and continuing to the present day, islands once occupied by rodents are now being reclaimed (Russell and Broome 2015). The tactical use of toxic bait to protect island populations of indigenous birds, reptiles, and invertebrates endangered by rats and mice continues to be refined to enable larger and more complex islands to be cleared of rodents. These endeavours are part of global efforts to eradicate invasives and manage islands to protect native birds and other important fauna and flora (Clout 1999).

Another example of improved utilisation of individual tools can be illustrated by the more targeted application of 1080 baits. The aerial 1080 technique has been steadily improved over the last 60 years. The method was introduced in the early 1960s with an initial focus on developing palatable baits and improving carrot cutters to remove fragments that were attractive to birds. Sowing rates were initially very high at over 30 kg/ha. During the next three decades, Morgan et al. (2004) showed that accurate delivery using emerging GPS technology and improved sowing buckets would increase kills to over 90% and enable a massive reduction in bait used (i.e., to less than 5 kg/ha). In the early 1990s, high application rates of up to 15 kg/ha of 1080 baits were still being used in New Zealand for possum control. High sowing rates were primarily used because baits were variable in size, toxicity, and palatability, and were distributed unevenly (Morgan 2004). Once bait less likely to crumble during distribution became available, it was possible to reduce sowing rates and explore more targeted bait delivery patterns (Nugent et al. 2008). Over a decade ago, sowing baits at 3 kg/ha was shown to be as effective as at 10 kg/ha, and even lower rates have been achieved since.

For the last three decades, a focus has been on the retention of product registrations for existing older pesticides and bait products (Eason et al. 1999, Adams 2005, APVMA 2008, Eason et al. 2011). In contrast to many other countries, in particular those in the EU, which are almost entirely reliant on anticoagulants, the US and New Zealand have worked to retain registrations; New Zealand has retained the use and registration of cyanide and 1080. Both compounds played an important role in mammalian pest control in New Zealand for several decades (Eason et al. 2010) and continue to do so. 1080 was subjected to a re-registration process in 2006 and 2007. Aspects of the research which underpinned the NZ EPA approval were quality assurance of baits, reduced sowing rates of 1080, and improved understanding of 1080 toxicology.

Despite the re-registration of 1080 in New Zealand there still remain concerns over how it is used, and with the emergence of resistance to second-generation anticoagulants in some populations of rodents, as well as residues in wildlife being identified globally (Young and De Lai 1997, Stone et al. 1999, US EPA 2004, US EPA 2008), interest in non-anticoagulants (or at least less persistent low residue vertebrate pesticides) has been revived and more new acute substances have been investigated (Eason et al. 2013, Eason et al. 2014, Shapiro et al. 2015, Eason et al. 2017). This interest has been coupled with the questionable humaneness of second-generation anticoagulants in larger vertebrate pests (Littin et al. 2002) and has led to research and

development focused on new toxins, more effective lures, resetting systems, and remote sensing.

Norbormide is an example of a unique species-specific rodenticide, currently undergoing further development, which is covered (e.g., papers in these Proceedings). Para-aminopropiophenone (PAPP) and sodium nitrite are examples of the development of new compounds. PAPP was registered for the control of stoats (*Mustela erminea*) and feral cats (*Felis catus*) in April 2011 (see Eason et al. 2014); it is now also registered in Australia. Sodium nitrite was registered in 2014 for control of possums and feral pigs (Shapiro et al. 2015) and is currently undergoing research for registration in the US for feral pig control. PAPP and sodium nitrite have been termed red blood cell toxins, due to their mode of action through induction of methaemoglobinaemia (Eason et al. 2017). Desirable features of these new toxins are: 1) they are lethal to the target species, 2) they are relatively humane, 3) they are orally active and rapidly absorbed, 4) they have relatively short half-lives in blood/organs, 5) they are not persistent in the environment, 6) they do not lead to secondary poisoning, and 7) they have an antidote or do not need one, in the case of norbormide. Also, a low dose of cholecalciferol as an additive to diphacinone (D+C) is being researched in both the US and New Zealand. This is a potential alternative to brodifacoum where bioaccumulation of residues and non-target effects are a concern (Crowell et al. 2013).

New resetting toxin delivery systems are still of interest, although research has temporarily slowed in New Zealand due to reduced support. These devices allow for multiple pest animals (~200) to be killed with a single device whilst incorporating responsible toxin delivery techniques (i.e., low risk to non-targets). These devices, built on earlier prototypes (King et al. 2001, King et al. 2006), are showing promise in field trials (Blackie et al. 2013, Blackie et al. 2016, Murphy et al. 2017). Crucial future steps include commercialisation of prototypes; completing registration of toxins and resetting devices for rodents, mustelids, feral cats, and possums; and more extensive and vigorous field testing of efficacy in different control and eradication scenarios. Research into optimum spatial deployment strategies, aimed at minimising device spacing and numbers of servicing visits, still needs to be conducted.

New research on lures is underway and critically important. This is because, as mentioned earlier, there have been no tangible advances in this field for over 100 years: lures for vertebrates are commonly foods like peanut butter or food-based pastes and these are perishable and require frequent replenishment, factors that increase control operation costs and decrease control operation efficacy (Jackson et al. 2015).

In the last 10 years, automatic resetting traps have been advanced and improved. Goodnature Ltd (NZ), working with the Department of Conservation, has designed new devices that kill animal pests and then reset themselves (Gillies et al. 2012). Targeted species include stoats, rats, and possums. Field experience continues to be gained alongside improvements in engineering design; however, funding for what was emerging as an integrated approach has been reduced since 2015 (Eason et al. 2017).

Other recent innovations include improving the design of standard kill traps, and live-capture traps coupled with wireless technology to make monitoring and control far more effective and substantially cheaper (Jones et al. 2015). These approaches are being pioneered by ZIP Ltd (AU), which has been established as a research and development company to advance new approaches to predator management. A practical remove-and-defend strategy has evolved, with intensive use of traps to enable the complete removal of rats, stoats, and possums from large areas, and then defend them from reinvasion with a focus on refinements of a barrier system and detection of very low numbers of predators when they do breach barriers. Research and practical experience provides a platform for extending this approach to larger and larger areas (Al Bramley and Devon McLean, pers. comm. 2016)

2018-2050

Despite recent advances, decades old broad-spectrum toxins and traplines are still the mainstay of pest control (Hansford 2016). A technological leap is needed to achieve much more precise, affordable, and socially-acceptable pest control systems deployable at great scale across urban, rural, and wilderness landscapes. The period 2018-2050 should be a new period for accelerated innovation. There are exciting opportunities in the future for transformational change based on replacing siloed thinking with collaboration, and the integration of existing and new tools and technologies. In practical terms this will involve completing the development and validation of individual technologies; then reaching beyond current approaches and optimising cost-effective procedures for integrating traditional methods (e.g., toxin baiting) with recently developed approaches such as species-specific toxins, potent lures, real-time monitoring, drones, technologies from completely different fields such as AI and IoF, big data handling, and testing at local scale as a platform for landscape scale extrapolation. Emerging technologies still requiring significant research and development include advances in wireless technology for species recognition; the next generation of self-resetting traps; unmanned aerial vehicles (UAVs); and improved species-specific toxin-delivery systems (Murphy et al. 2018) enhanced with advanced lures and new toxins to combine low-residue characteristics with selectivity and humaneness (Eason et al. 2017). UAVs may soon have the capability of carrying >15-kg payloads to deliver precise amounts of toxin to exact locations to target pests (Morley et al. 2017). Flying at beyond visual line of sight (BVLOS) may also be rapidly resolved with sophisticated technological advances and improved regulations, if potential risks are mitigated (Philip Solaris, X-Craft Ltd., pers. comm.). In the future, field research that tests individual technologies should be replaced with integrated technology research, developed for workable in-field strategies. The benefits of new science operating in this way with integrated multi-technology products (rather than single technologies)

could be highly significant.

There are many examples which will benefit from this approach. There are aspirations to combine resetting toxin-delivery systems with species recognition to improve specificity for New Zealand and overseas markets. Analysis of footprint, gait, and stride length will allow for real-time mammalian species discrimination as individuals cross a waterproof, low-cost sensing surface (Blackie et al. 2017). Work is now underway on species-specific traps that activate following on-board processing to identify the species. Semiochemical-based lures, when combined with effective delivery technologies, will provide controlled odour release and long life, factors that will help expand the utility of resetting toxin-delivery systems and traps (Jackson et al. 2016). Ultra-potent lures should expand the range and cost-effectiveness of monitoring devices, resetting toxin-delivery systems, and traps. A long-distance lure is clearly a critical requirement for any minimal-spacing array; the cautious behaviour of pest animals towards artificial devices is also a serious issue requiring integrated research.

A recent international review paper concluded that these types of developments offer "transformational change" in pest control (Campbell et al. 2015), but this will only be the case if these developments can be integrated into a landscape-scale strategic framework and if more practical field experience is gained. For example, whilst there have been decades of continuing investment and hundreds of papers on field use of 1080, there are only two publications reporting the field application of PAPP for predator control in New Zealand (Dilks et al. 2014, Murphy et al. 2017).

LESSONS FROM THE PAST – OPPORTUNITIES FOR THE FUTURE?

Arguably the past decades have seen only slow advancement of technology, with disproportionate focus on population biology research (Simberloff 2003). A sharpened and more intense sustained-technology focus is needed. There will be risks associated with any research, and not all technologies entering a research and development and commercialisation pipeline will succeed. By implementing an integrated approach, i.e., not putting all the eggs in one basket, we propose advancing a suite of complementary technologies. In the same vein, over-reliance on single-solution technologies for small mammal pest control is the wrong approach for biodiversity conservation. This has been demonstrated through two decades of challenging research on viral vectored immunocontraception. While contraceptive vaccines can be delivered remotely, they still require administration to each individual animal that is intended to be made infertile. Thus, contraceptive vaccines have been used to control only relatively small populations of wildlife. Virally vectored immuno-contraception was discontinued after 20 years of imaginative and multidisciplinary research which unfortunately failed to deliver (Tydale-Biscoe and Hinds 2007), after trans-Tasman and US investment exceeding US$80 million (Steve Lapidge, formerly Invasive Animal CRC, Australia, pers, comm.).

New non-lethal control of vertebrate and invertebrate pests (i.e., the Trojan Female Technique) are being considered. Naturally occurring mutations that could cause male infertility in the maternally inherited mitochondrial DNA could be enhanced. These mutations have been identified in fruit flies and mice and are likely to be widespread in nature. Research aims to harness this for mammalian pest control. In this field, an international consortium named GBird (www.geneticbiocontrol.org), has been formed to bring together the suite of skills needed to address these challenges. Technical approaches currently being investigated include the production of strains of mice who carry altered genes that determine sex. The intent is to create a mouse that produces either only male or infertile female off-spring with the goal of skewing the sex-ration, leading to population collapse and enabling eradication of mice from island ecosystems.

There are numerous knowledge gaps (Moro et al. 2017) which are challenging, and acknowledging and assessing the risk of gene drive technologies will be critical. Researchers in the field are mindful of the need for transparency. There is a danger that gene editing, which may have many uses in the future, will be seen as panacea for control of all mammal pests. Hence, it is timely to learn from the past, taking a measured approach with a focus on social engagement, communication, outreach, ethics, risk assessment and biosafety. Equally important will be lateral thinking, wherein a better understanding of the unique genetic makeup of pest species leads to other developments such as species-specific toxins (Brian Hopkins, Landcare Research, pers. comm.)

Regardless of the challenges and caveats, research around the feasibility of new ideas should continue (Moro et al. 2017). A broader strategy for mammalian pest control should explore biocontrol (including rabbit haemorrhagic disease; Eden et al. 2015) and gene editing (Thresher et al. 2014, Ganzt et al. 2015, Moro et al. 2017), complemented by further research and development into, and practical field experience with, integrated emerging technologies. In the field of rodent and vertebrate pest control, failure to retain and improve existing pesticides and other novel tools for the next decade could have serious consequences.

CONCLUSIONS

Traps and older poisons such as red squill, arsenic, and cyanide have been used for hundreds if not thousands of years. More recently, from 1940 to 1980, there was a period of innovative chemistry with the discovery of new molecules, including acute toxins and slower acting anticoagulants. The period 1980 to 2017 represents a time of innovation in terms of field practitioners' improving utilization of individual tools and researchers' understanding and mitigating of side-effects (Eason et al. 2013). Researchers and registration specialists improved registration dossiers and retained or lost registrations in different jurisdictions (Eason et al. 2010, Eason et al. 2017). Progress has been made in the development of pest surveillance; new toxins, lures, and delivery systems; and exploration of non-lethal control options. However,

the technical advances have occurred somewhat in isolation, lacking integration and systematic thinking. Recently, a three-pronged strategy was evolving to 1) improve the use of existing tools, 2) develop advance emerging technologies, and 3) practice fundamental research on new ideas (Eason et al. 2017). This approach has stalled, with greater reliance on new "silver bullet" technologies or the advancement of individual technologies in isolation. On reflection, the three-pronged approach is probably outdated and requires new strategies and thinking to replace the segregated vision with a more integrated one that utilizes new tools and technologies.

Over future decades, during 2018 to 2050, there should be a new period for accelerated innovation. In practical terms, this will involve completing the development and validation of individual technologies, then optimising cost-effective procedures for integrating traditional methods of toxin baiting and trapping with recently developed or developing approaches. This should lead to a reduction in the need for conventional aerial application of baits, which, of all the current control methodologies, continues to cause greatest concern (Hansford 2016, MacDonald 2017).

When assessing control technologies for integration, it is important to recognise that some, like 1080 baiting, have been researched and refined at considerable expense for over 65 years. New technologies, whether they be new toxins such as PAPP (Eason et al. 2014), better traps (Barr et al. 2011), resetting toxin delivery systems, or various genetic manipulations (Gemmell et al. 2013, Moro et al. 2017), badly need focused and completed research. This should be followed by extensive management experience for an appropriate assessment of what is the best option or where different technologies might offer most benefit. There has been limited practical experience with emerging technologies compared with anticoagulants or older toxins and additional practical experience is imperative, at this stage, to enable the potential of new toxins and other tools to be realised through synergistic application strategies. We propose the concurrent development of a suite of emerging technologies as complementary components in an automated and integrated pest management system. Specifically there are future opportunities to advance more humane and species-specific toxins and baits, super-lures and bait-consumption motivators (i.e., long-life semio-chemical social and food signals), multi-kill devices and species recognition devices (digital print acquisition for wildlife surveillance), and drone bait-delivery systems within an automated remote communications and decision-making artificial intelligence network handling big-data for real-time decision-making and pest-control responses.

Disruptive technology can displace current technology in ways that the market does not expect, and in mammalian pest control we need this effect, along with step-wise improvements that can be achieved in the short and medium term. Importantly, the critical capabilities needed to deliver and ensure the continued improvements are: collaboration across disciplines; hands-on experience of research in science or engineering disciplines relevant to product development and commercialisation; and practical wildlife management experience (Allen et al. 2013). Once established, some of these technologies and integrated approaches should have global application beyond conservation in agricultural and urban settings.

We still believe that continued fundamental research is very important, but not at the expense of the integrated approaches described in this paper. Our aspiration is to achieve endangered species protection through optimum use of existing tools with development and uptake of promising emerging and new technologies for the control of rats, stoats, feral cats, and possums. We believe that science and technology has now advanced such that automated, online, and real-time systems for monitoring and managing pests are achievable in the next decade.

ACKNOWLEDGEMENTS

MPI, MBIE, Regional Councils, OSPRI, Connovation Ltd and Department of Conservation, NZ and many collaborators in New Zealand and internationally including the organisers of the VPC Conferences and Editor of the Proceedings Publications.

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